

## TEMPORAL DISCRIMINATION LEARNING OF OPERANT FEEDING IN GOLDFISH (*CARASSIUS AURATUS*)

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Operant temporal discrimination learning was investigated in goldfish. In the first experiment, there was a fixed daily change in illumination. Eight subjects were trained to operate a lever that reinforced each press with food. The period during which responses were reinforced was then progressively reduced until it was 1 hr in every 24. The final 1-hr feeding schedule was maintained over 4 weeks. The feeding period commenced at the same time each day throughout. The food dispensers were then made inactive, and a period of extinction ensued for 6 days. The pattern of responding suggested that the fish were able to exhibit temporal discrimination in anticipation of feeding time. This pattern of responding persisted for a limited number of days during the extinction procedure. The second experiment produced evidence that operant temporal discrimination could develop under continuous illumination.

*Key words:* temporal discrimination, anticipation, feeding schedules, time of day, fixed-interval schedule, lever press, goldfish

Temporal rhythms are evident in the day-to-day behavior of nearly every living organism. Sometimes these rhythms result from simple reactions to regular environmental events, but often they appear to involve some innate timing mechanism (Cloudsley-Thompson, 1980).

The ability of mammals to apply discrimination of intervals in the order of hours to the regulation of operant responding is well established (Armstrong, 1980; Boulous & Terman, 1980; Terman, Gibbon, Fairhurst, & Waring, 1984). Although there have been a number of studies that have demonstrated that fish will learn operant responding under the control of visual or acoustic discriminative stimuli (Abbott, 1972; Tennant & Bitterman, 1975; Wright & Eastcott, 1982) and short-interval temporal stimuli (Rozin, 1965), there are no reports of operant responding during long-interval temporal stimuli. However, in their natural environment, many species of fish do coordinate their activity with diurnal rhythms such as the onset of dawn and dusk (Müller, 1978).

Classically conditioned, temporally coordinated feeding has been observed in aquarium-

housed killifish (*Fundulus heteroclitus*) and bluegills (*Lepomis macrochirus*) (Davis & Bardach, 1965). These subjects were exposed to artificially controlled light cycles and were fed by hand at fixed times each day. The fish were given no external cue other than a regular feeding schedule and the amount of time elapsed (typically 6 hr) since the lights were turned on. It was found that regular regimes resulted in distinct bouts of activity that anticipated feeding time. Subsequent shifts in light onset and feeding times resulted in corresponding shifts in prefeeding activity after 1 to 3 days of exposure. Further experiments demonstrated that a prefeeding response developed even when fish were kept in continuous light (as long as food was delivered at regular intervals).

Davis and Bardach (1965) suggested that the prefeeding response was the result of the association between the act of feeding and the phase of an endogenous rhythm. Because the time of the prefeeding activity could be affected by altering the time of the onset of light, they hypothesized that this feature of the environment, although not essential, could be used in conjunction with the regularity of the feeding times to coordinate the endogenous rhythm.

Although Davis and Bardach (1965) did not make food contingent on the behavior of their subjects, several studies of acoustic conditioning (Abbott, 1972; Fujiya, Sakaguchi, & Fukuhara, 1980; Midling, Kristiansen, Ona, & Oeiestad, 1987; Wright & Eastcott, 1982) have shown that fish will learn an operant response

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in regimes that feature some temporal regularity. However, these experiments were not directed at temporal discrimination, and so the temporal contingencies were confounded with immediate, exogenous, acoustic cues.

The present experiments investigated long-interval temporal discrimination in the absence of such cues. In Experiment 1, aquarium-housed goldfish were trained to press a lever in order to activate a food dispenser that was operational only at certain fixed times. The only predictive external cues were the temporal regularity of the light cycle and feeding schedule. If time served as a discriminative stimulus, the number of lever presses immediately preceding these feeding periods would be expected to be higher than at other times during the temporally restricted feeding regime, and indeed, higher than at any time during a temporally unrestricted feeding regime. Further evidence of temporal discrimination would be provided if, when feeding is temporally restricted, there was less lever pressing at times other than those preceding the feeding periods than there was at equivalent times when feeding is unrestricted. In other words, if feeding time becomes a positive discriminative stimulus, then times not associated with feeding should take on the properties of a negative discriminative stimulus.

## EXPERIMENT 1

### *Method*

**Subjects.** The subjects were 8 goldfish (*Carassius auratus*), with a mean standard length of 9.75 cm ( $SD = 1.3$  cm), obtained from J & K Aquatics Ltd., Wellington, Somerset. An additional 8 goldfish of a similar size were used as "companion" fish (see below) but did not contribute to the data. Prior to the experiments, the fish were not kept on any fixed feeding regime or used in any other experiments. All animals used in these experiments were treated in accordance with the "Ethical Principles of Psychologists" (American Psychological Association, 1981).

Goldfish are an ornamental cultivar of the cyprinid family. Feral populations usually inhabit shallow, densely vegetated pools with muddy bottoms and diversified shorelines (Lek, 1987), and feed on a broad range of food types, including plants, insect larvae, and plankton (Wheeler, 1978). Because goldfish

have no stomach, their capacity for storing food is limited. When food is continually available, they tend to feed for extended periods rather than taking distinct meals (Rozin & Mayer, 1961). Studies of the relation between the light cycle and the pattern of free feeding (Rozin & Mayer, 1961) and activity (Spoor, 1946) in goldfish have shown a measure of variability among individual subjects. Most are predominantly diurnal, but some display patterns that are predominantly nocturnal, and others show no fixed pattern at all.

**Apparatus.** The fish were housed in glass aquariums (90 cm by 30 cm by 38 cm). Following an initial training stage, each aquarium was divided in two by a plastic grill placed across the center of the longest side. The aquariums were screened off from each other with opaque plastic sheeting. The water was maintained at 20 °C and was aerated and filtered using standard laboratory equipment. Cleaning of the aquariums took about 10 min and was carried out approximately once every 3 days, between 9:00 a.m. and 12:30 p.m. or 2:30 p.m. and 7:00 p.m. The precise time (within these limits) was varied.

A food dispenser controlled by a fish-activated lever was mounted at one end of each aquarium. The lever consisted of a stainless steel rod (20 cm long, 0.3 cm diameter) with the lower tip sleeved with thick-walled silicone rubber tubing (0.4 cm diameter). This projected approximately 0.5 cm below the water surface, 8 cm to the side of the point where food was dispensed. The rod was held in a near-vertical position and pivoted 7 cm from its lower tip. When the lower end was moved, the upper end passed through an opto-electrical sensor that was connected to the control equipment. The fish activated the lever by pushing the lower tip 0.75 cm forward with its mouth. In order to reactivate the lever it had to be released, at which point gravity returned it to its resting position. A force of at least 0.0004 N was required to activate the lever. This was sufficient to prevent activation by water movement.

Two distinct lever-pressing techniques have been observed with this apparatus. Fish either make a single press by swimming up to the lever, pushing it, releasing it, and then swimming around in an arc to consume any food that has been dispensed or to prepare for the next activation, or they remain stationary in

front of the lever and make repeated activations, using their pectoral fins to move forward and backward the required distance.

The dispensers were actuated by a 0.5-s pulse of power to a 22-V solenoid. This moved a sliding plate away from an aperture in the base of a food hopper. The plate was returned to its resting position by means of a steel spring. The size of the aperture was adjustable, and for these experiments it was set to dispense approximately 0.05 g of Hikari staple fish diet (a floating fish food) in the "baby" pellet size on each activation. The need for a 0.5-s pulse of power to activate the dispensers meant that the maximum rate at which reinforcement could be delivered was restricted to 120 per minute. In practice, the rate of responding never approached this figure. The food was delivered to a point 12 cm inward from the center of one end of the aquarium. A second dispenser was mounted in a similar position at the other end of each tank. The second dispenser was activated simultaneously with the first and was not supplied with a separate lever.

One additional dispenser was mounted in a narrow space between the rows of aquariums and was set to operate in randomly spaced bursts of up to 20 activations. This "decoy" feeder was used to reduce the availability of systematic, temporal cues from the sound of dispensers operating in adjacent aquariums. No food was provided by the decoy dispenser.

The control and recording system consisted of a BBC Model B microcomputer and an interface device. This allowed the experimenter to set the times during which activation of the lever would result in food being dispensed; the equipment also recorded the time of occurrence of all lever activations.

Lighting was provided by two 15-W fluorescent bulbs mounted directly above the aquariums. These were operated by a time switch that turned the lights on at 8:00 a.m. and off at 8:00 p.m. each day. In addition, an 11-W incandescent bulb was situated between the fluorescent bulbs and was left on continuously to provide low-level illumination even when the main lighting was switched off. A fixed daily light cycle was used in this experiment because Davis and Bardach (1965) suggest that this provides optimum conditions for the development of temporally coordinated prefeeding behavior. Light intensity at the water surface was 302 lx when the fluorescent

bulbs were switched on and 12 lx when they were off.

The experiment was housed in a laboratory that was isolated from main corridors and was rarely used by other workers. The windows were covered with foil to block light from outside. The possibility that environmental disturbances beyond the control of the experimenters (e.g., traffic noise from the road outside) could be perceived by the fish cannot be ruled out. Although these were not apparent to the experimenters and were probably masked by noise made by equipment (pumps and filters), the experimental procedures were designed to reduce the possibility of such environmental stimuli being coordinated with relevant experimental events.

*Procedure.* The apparatus was set so that each lever press produced food at any time. One subject was placed in each of the tanks together with another fish. This second fish had not experienced any restricted feeding regimes but was already a reliable lever presser. This gave the opportunity for the subject fish to acquire the lever-pressing response through observational learning (Yamagishi & Nakamura, 1981). All subject fish were observed to be lever pressing within 7 days.

The experiment was divided into four stages. The first stage lasted 14 days and was designed so that the baseline feeding rhythms of the subject fish could be determined. The plastic grill was used to partition the tanks, with 1 fish in either end. Only the subject fish had access to the lever, but any presses activated both dispensers. This arrangement removed the need to feed the companion fish by hand and thus kept disturbances to a minimum. The "companion" fish is so termed because its role was to prevent the subject from exhibiting the alternating stereotypy and inactivity often observed in goldfish that are kept for extended periods in total isolation. Visual, auditory, and olfactory contact between the 2 fish remained possible despite the presence of the barrier.

The second stage involved restricting the periods when a lever press would be reinforced to a single 1-hr interval in each 24-hr period. These periods (feeding times) were timed to commence 6 hr after the lights were switched on for Subjects 1, 3, 5, and 7 (2:00 p.m. to 3:00 p.m.), and 6 hr after the lights were switched off for Subjects 2, 4, 6, and 8 (2:00 a.m. to 3:00 a.m.). The feeding time for Sub-

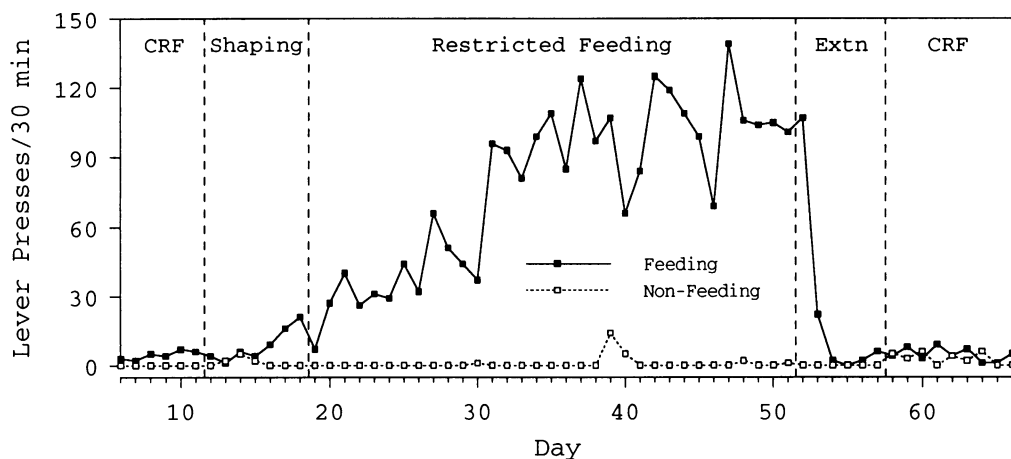


Fig. 1. Subject 5. Sum of lever presses during the 30 min immediately preceding the designated feeding time (2:00 p.m. to 3:00 p.m.) and nonfeeding time (2:00 a.m. to 3:00 a.m.), starting with the last 6 days of the first baseline stage (Stage 1, CRF), through the shaping of the restricted feeding schedule of Stage 2, and the 6 days without food (Stage 3, Extn), to the first 9 days of the second baseline (Stage 4, CRF). The ordinate axis is slightly displaced to allow inspection of the lower values; the abscissae denote the number of days since the start of Stage 1.

jects 1, 3, 5, and 7 was designated a nonfeeding time for Subjects 2, 4, 6, and 8 (and vice versa) for the purpose of analysis. Separate feeding times for different subjects were used to avoid the possibility of a regular external event being used to coordinate responses by all of the subjects.

The transition from continuous to restricted feeding was carried out over several days by restricting the period during which the dispenser would respond to a lever press to 12 hr on the 1st day and thereafter reducing the feeding period by 2 hr per day (provided that the subject had responded during the previous day's feeding period). These periods always began at the beginning of the target period. This procedure resulted in a progressive lengthening of the interval between periods of food availability while maintaining the temporal location of the start of those periods. The shaping process was necessary because there was no guarantee that responding would occur during the target period if the transition to restricted food availability was made directly. If all responses occurred outside the feeding times, the operant would rapidly extinguish. Once the subjects were responding during the target hour, they were kept on schedule for a further 4 weeks.

The third stage consisted of an extinction test, in which the dispensers were disabled for 6 consecutive days.

The fourth stage involved a return to continuous food availability. This was done to in order to see if the restricted feeding regimes had produced any permanent effects on baseline responding. This stage lasted for 2 weeks.

Data were collected continuously, and were recorded as the total number of lever presses in each consecutive 15-min period.

### Results

Subject 4 died of a bacterial infection, but the remaining 7 subjects all reached a stable level of responding during the period of unrestricted feeding (Stage 1). Subjects 2 and 7 displayed some evidence of a feeding rhythm during Stage 1. In order to attenuate any effects of preferred feeding times on responding during the restricted feeding stage (Stage 2), these subjects were subsequently allocated to feeding times during which baseline responding had been less frequent.

Figures 1 and 2 show the development over days of the effects of the contingencies of the various stages of Experiment 1 on lever pressing during the 30 min immediately preceding the feeding and designated nonfeeding times for Subjects 5 and 6, respectively. The response patterns of these subjects were typical of subjects feeding in the photophase (Subjects 1, 3, 5, and 7) and scotophase (Subjects 2, 6, and 8), respectively. Following the restriction of the feeding periods to 1 hr in Stage 2, the

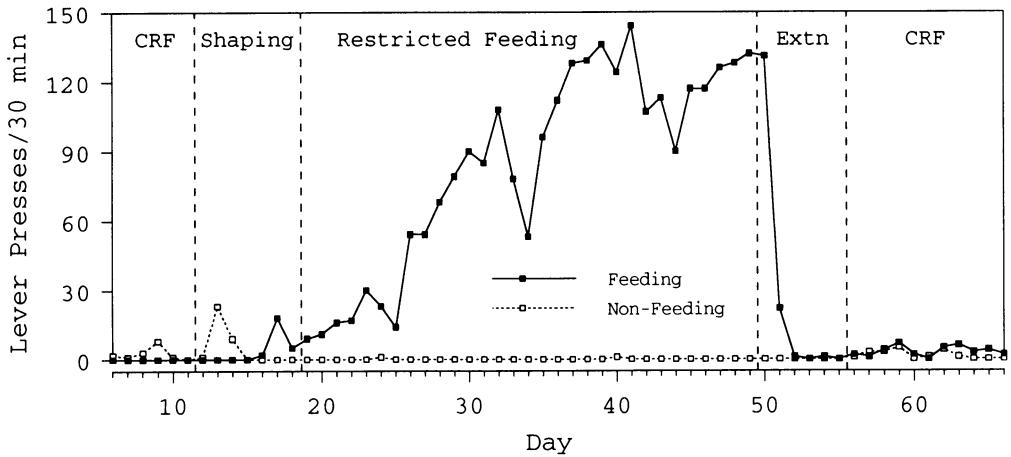


Fig. 2. Subject 6. Details as in Figure 1, except that the designated feeding time was from 2:00 a.m. to 3:00 a.m., and the designated nonfeeding time was from 2:00 p.m. to 3:00 p.m.

pattern of responding altered markedly. The rate of responding prior to the feeding times increased rapidly and then reached a more or less stable level after a period of about 20 days. The rate prior to the designated nonfeeding times remained close to zero throughout.

The mean level of lever pressing over five successive 24-hr periods on the initial baseline, restricted feeding, and final baseline schedules (Stages 1, 2, and 4) of the experiment are also given for Subjects 5 and 6 in Figures 3 and 4,

respectively. Typically, a fairly constant rate of three to five presses per 15 min throughout each 24-hr period was observed during Stage 1. When a stable pattern of responding had been reached in Stage 2, a typical daily record showed a level of responding that was close to zero until between 4 and 6 hr before food became available. Once responding had begun, the rate accelerated almost linearly with time until it reached a level of approximately 40 responses per 15 min immediately prior to

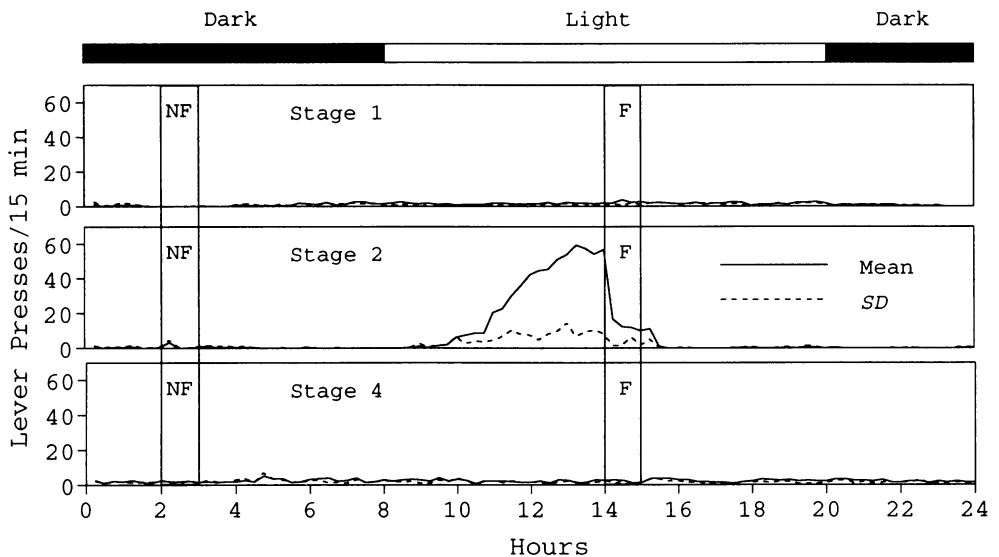


Fig. 3. Subject 5. Mean and standard deviation of lever presses per 15 min over the last 5 days of Stages 1 and 2 and the first 5 days of Stage 4. The vertical bars indicate feeding (F) and nonfeeding (NF) periods. The lighting regime (main lights on at 8:00 a.m. and off at 8:00 p.m.) is indicated by the horizontal bar at the top.

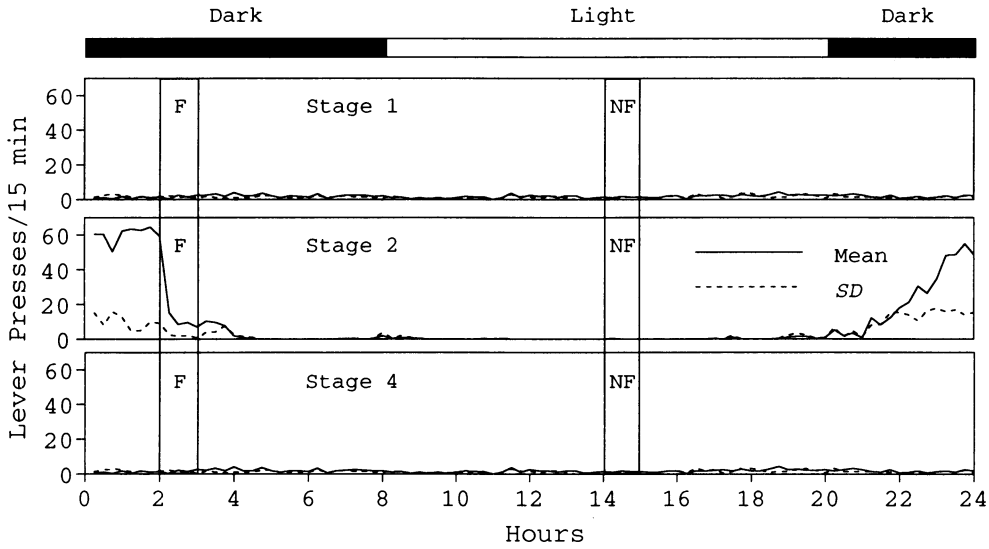


Fig. 4. Subject 6. Details as in Figure 3.

feeding. During the hour of food availability, the rate of responding dropped to around 10 presses per 15 min, and then dropped back to zero within an hour of the end of the feeding period.

The mean level of responding during the 30 min prior to feeding and designated nonfeeding times over the final 5 days in Stages 1 and 2 and the first 5 days in Stage 4 is given for all subjects in Table 1. A repeated measures two-

way analysis of variance (ANOVA) was carried out on these data. All data were square-root transformed to stabilize variance. All significance levels were adjusted using Hunyh-Feldt epsilon. There was a statistically significant effect of Stage,  $F(2, 12) = 61.02, p < .0001$ , and of Time of Day,  $F(1, 6) = 119.72, p < .0001$ , on the mean number of lever presses recorded during the 30 min immediately prior to the feeding and nonfeeding times. The interaction between the number of lever presses prior to feeding and nonfeeding times and the three stages was also statistically significant,  $F(2, 12) = 52.35, p < .0001$ . Examination of the planned comparisons of means was carried out using the "contrast" facility on Super-ANOVA software (Abacus Concepts, 1989). The level of responding prior to feeding and nonfeeding times during the two baseline stages was not significantly different: Stage 1,  $F(1) = 0.06, p = .72$ ; Stage 4,  $F(1) = 0.43, p = .46$ , but there were significantly higher response levels prior to feeding times during the stage of restricted feeding (Stage 2) than prior to all other times in all stages,  $F(1) = 216.74, p < .0001$ .

There was a lower mean rate of responding prior to the nonfeeding time during the restricted feeding stage (Stage 2, a mean of 0.31 presses per 30 min) when compared with the baseline level of responding (feeding and nonfeeding times in Stages 1 and 4, a mean of

Table 1

Number of responses in the 30 min prior to the feeding (F) and nonfeeding (NF) periods of Experiment 1.

Subject	Stage 1		Stage 2		Stage 4	
	F	NF	F	NF	F	NF
1	M	0.8	0.0	42.4	0.0	2.6
	SD	0.4	0.0	9.3	0.0	1.8
2	M	0.0	6.8	88.0	0.0	5.0
	SD	0.0	1.8	9.5	0.0	4.3
3	M	2.0	0.4	81.8	0.4	2.2
	SD	1.0	0.9	33.3	0.5	1.6
5	M	3.6	0.0	111.0	0.6	5.6
	SD	1.1	0.0	15.8	0.8	2.7
6	M	0.0	3.8	124.0	0.0	2.3
	SD	0.0	2.7	6.7	0.0	1.6
7	M	0.6	3.0	57.0	0.0	6.0
	SD	1.3	3.1	12.3	0.0	3.9
8	M	3.8	1.2	37.6	1.2	4.8
	SD	2.9	2.7	12.4	1.6	3.3

Note. Values averaged over the last 5 days of Stages 1 and 2 and the first 5 days of Stage 4.

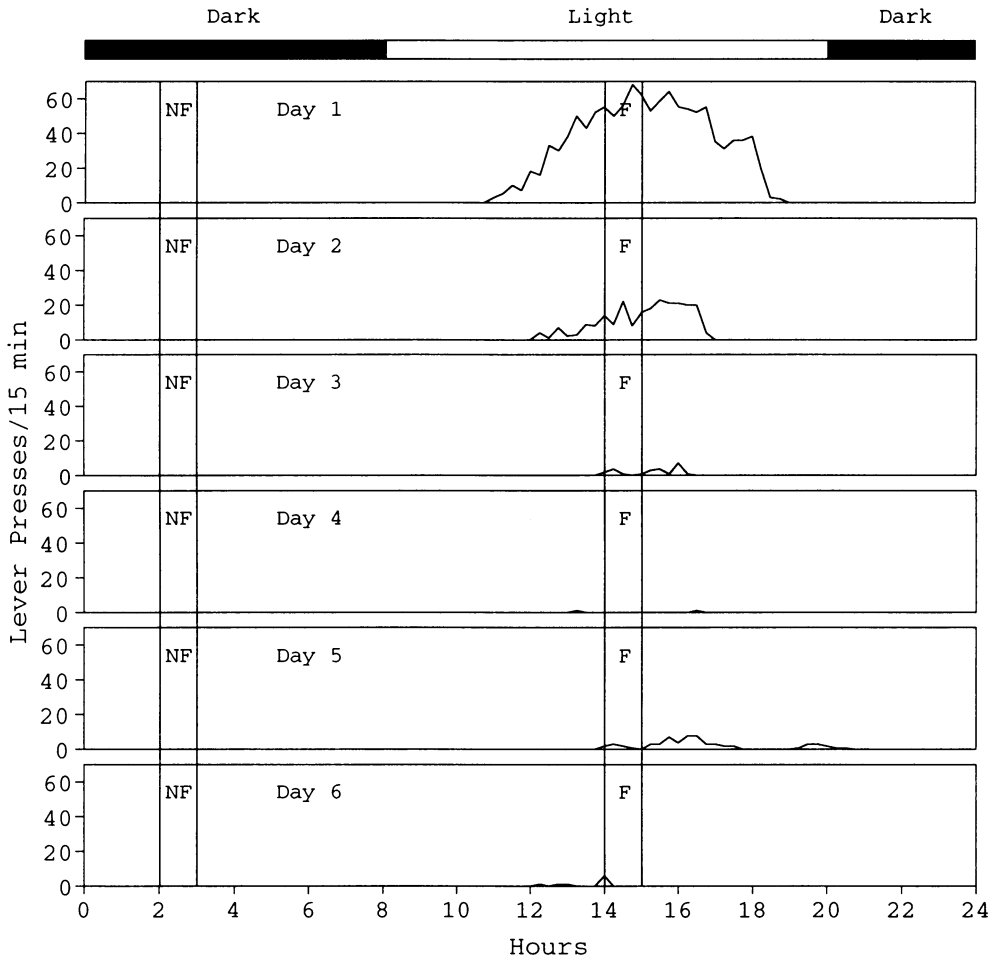


Fig. 5. Subject 5. Lever presses per 15 min over the 6 consecutive days of the extinction test (Stage 3). Bars indicate the feeding (F) and nonfeeding (NF) periods that had been in force in Stage 2. The lighting regime (main lights on at 8:00 a.m. and off at 8:00 p.m.) is indicated by the horizontal bar at the top.

2.67 presses per 30 min), but not to a degree that achieved statistical significance,  $F(1) = 4.34$ ,  $p = .08$ .

The mean level of responding during the 30 min prior to feeding times of the 3 subjects that fed during the dark phase of the light cycle was 83.2 ( $SD = 43.4$ ) and was 73.05 ( $SD = 30.07$ ) for the 4 subjects that fed during the light phase. A one-way ANOVA carried out on square-root transformed data suggested that no statistically significant differences in response rate were caused by this factor,  $F(1, 5) = 0.09$ ,  $p = .78$ .

The response patterns of Subjects 5 and 6 over the 6 days of the extinction test (Stage 3) are given in Figures 5 and 6. These patterns were typical of all subjects tested. Over the 6

days of the test, the pattern of responding became less clearly defined. For the first 2 days, a distinct aggregation remained around the times that had previously been feeding periods, but for the remaining 4 days, response rates dropped close to zero. However, any responses that were made tended to occur near the previous feeding time.

Once the subjects were returned to continuous food availability (Stage 4), responding quickly returned to levels and patterns that were nearly identical to those seen during the first baseline stage (Stage 1).

#### Discussion

The higher level of lever-pressing activity preceding the feeding time during restricted

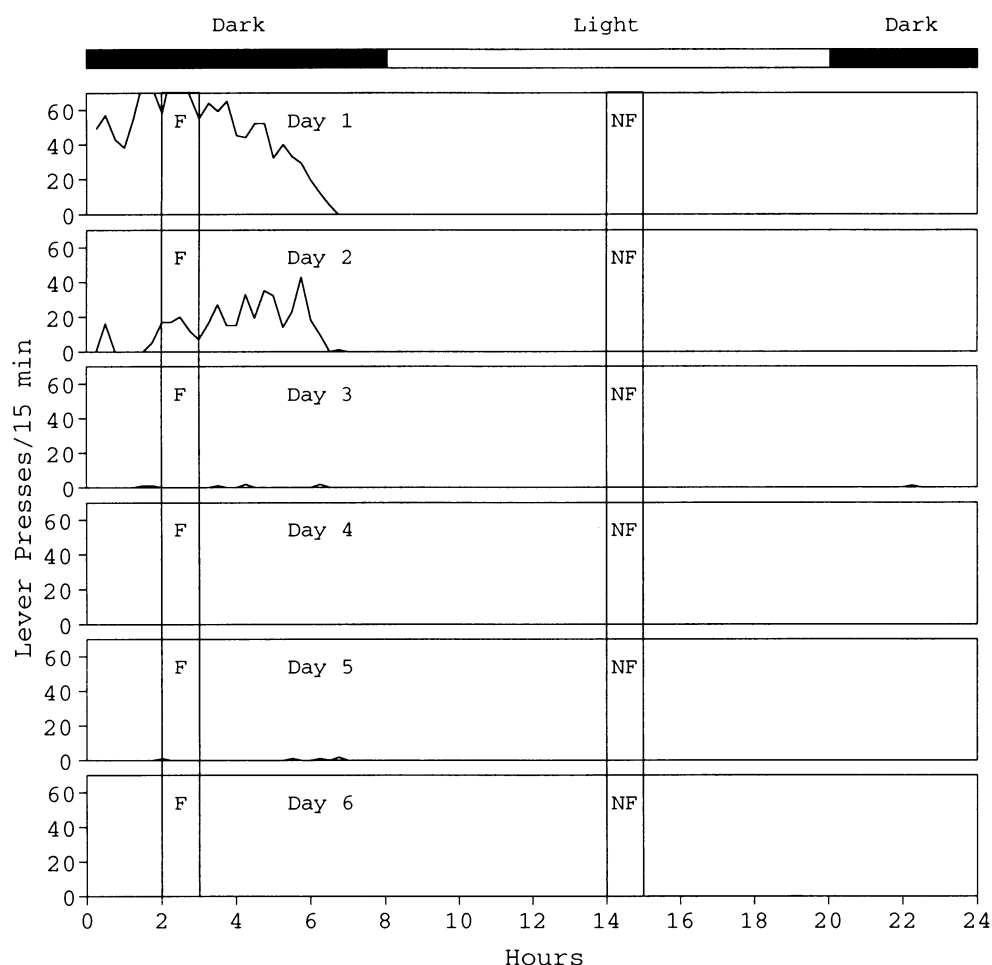


Fig. 6. Subject 6. Details as in Figure 5.

food availability (Stage 2) compared with levels prior to the nonfeeding time in the same stage and compared with baseline levels (Stages 1 and 4) strongly suggests that goldfish are capable of displaying operant temporal discrimination when the interval between opportunities for reinforcement is 23 hr. There was some support for the suggestion that nonfeeding times might take on the properties of a negative discriminative stimulus, because there was a lower mean rate of responding prior to the designated nonfeeding time of Stage 2 than during the equivalent period on the baseline phases. However, this difference did not reach statistical significance. It is possible that the lack of a significant difference was due to a "floor effect." The baseline levels were maintained at a rate from which it would be difficult to drop significantly lower.

The response rates associated with feeding times located in the middle of the photophase and scotophase were very similar. It is possible that uncontrolled regular external events allowed the subjects to anticipate these feeding times, but efforts were made to maintain a stable environment, and it seems unlikely that appropriate stimuli would have occurred before both feeding times. Further, no differences in responding were evident on weekends or during holidays (when the pattern of events outside the laboratory should have been different to that occurring on weekdays).

Figures 3 and 4 show that the rate of responding dropped dramatically at the onset of the feeding periods in Stage 2. This low rate continued throughout the time of food availability, then fell to zero an hour or so after the end of the period. The reason for the low level



of reinforced responding compared to the level of anticipatory responding may be that the subjects were spending time handling food and so had less time in which to activate the lever. During the approach to feeding time, there were no such distractions. It is equally true that there were no distractions following the feeding time, and although it is probable that motivational hunger would have been reduced by this time, an increased level of responding might have been expected. This lack of effect may be due to the subjects' behavior being controlled by the duration of the feeding period as well as the time of day at which it occurred. On the other hand, if this was the case, then it is difficult to see why the subjects continued to respond at all following the end of the feeding times, particularly when an unreinforced lever press indicated that reinforcement would not be available for another 23 hr.

Dews (1965) noted a similar phenomenon with pigeons on fixed-interval schedules of reinforcement when a negative discriminative stimulus was presented in alternation with a positive discriminative stimulus within each interval. The presence of the negative discriminative stimulus exerted a substantial inhibitory effect on responding, but this control was only slowly and progressively attained. If the nonfeeding period that followed the feeding period in the present experiment became a negative discriminative stimulus, it is possible that the continued responding (but at a decelerating rate) that followed the end of the feeding period represents a phenomenon of this type.

The key feature of the pattern of responding during the extinction stage (Stage 3) is that, although the magnitude of the response rate extinguished rapidly after the first 2 days, over those 2 days the temporal pattern remained remarkably constant (Figures 5 and 6). The 1st day on which reinforcement was omitted is functionally similar to a single unreinforced trial of the type used in the peak procedure (Catania, 1970). This procedure was devised as a method for obtaining a form of temporal generalization gradient that extends past the accustomed time of reinforcement. The conventional peak procedure provides data on the distribution of responding over time on unreinforced trials that are embedded within sessions on a fixed-interval schedule. These data are usually presented as the mean distribution

of responses from a number of unreinforced trials, so a direct comparison with the single trials presented here is not possible. However, the reasonably symmetrical shape of the distribution and the close proximity of the peak response rate to the expected feeding time are reminiscent of the response distributions obtained from pigeons on intervals of 10 s (Catania, 1970), 30 s, and 50 s (Gibbon & Church, 1990).

It could be that the decline in unreinforced responding over successive days in Stage 3 was simply due to inanition. The fish were given no food at all during this stage of the experiment and, because no measures of general activity were taken, no data are available to discount this possibility unambiguously. However, many species of fish undergo long periods of starvation in their natural environment (Larsson & Lewander, 1973), and goldfish have survived several months of starvation in laboratory studies (Love, 1980). Further, Spoor (1946) noted that, although activity declines markedly after a week of starvation, goldfish do not become completely inactive for more than an hour or two even after 2 weeks without food, and that activity levels return to those of unstarved fish within minutes of the reintroduction of food. In the present experiment the rate of reinforced responding also returned to levels similar to those of the first baseline stage soon after food was made available.

Even if the low rates of responding observed in the extinction stage had been a consequence of inanition, the finding that the anticipatory buildup persisted in the absence of reinforcement for at least 2 days suggests that the pattern of responses is unlikely to be entirely dependent on simple homeostatic or metabolic processes associated with increasing hunger or the emptying rate of the gut. This is concordant with the finding that short-interval operant temporal discrimination in goldfish is independent of simple metabolic rate. Rozin (1965) found no change in relative response rates on a fixed-interval 1-min schedule when ambient temperature was reduced from 30 °C to 20 °C. Goldfish are poikilothermic, and a decrease of this magnitude results in a halving of their metabolic rate.

A regular light cycle was used in Experiment 1 because Davis and Bardach (1965) found that this provided the optimum condition for the development of circadian temporal

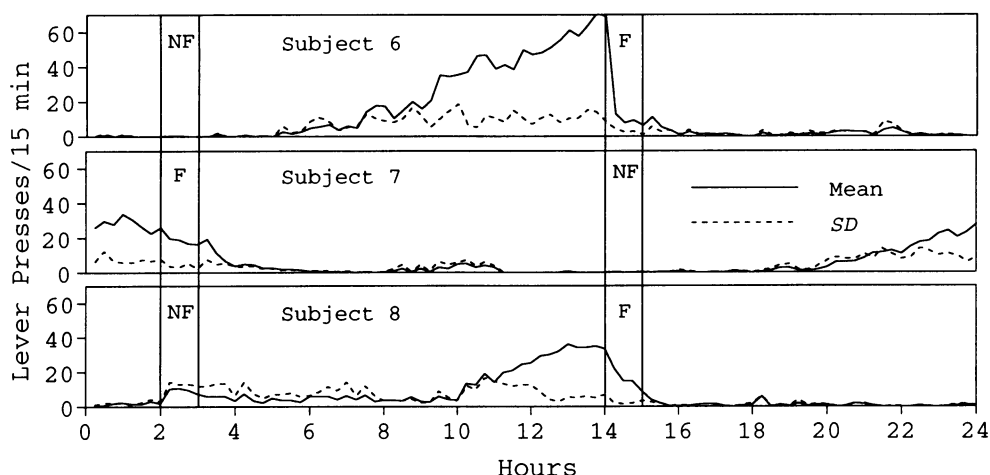


Fig. 7. Mean and standard deviation of lever presses per 15 min over the last 5 days of Experiment 2. Bars indicate feeding (F) and nonfeeding (NF) periods. The main lights were on continuously.

discriminations. They suggested that the light cycle may act as a zeitgeber, contributing to the regulation of a circadian timing mechanism on which the discriminations are then based. Whether or not this is so, the presence of a light cycle in Experiment 1 does leave open the possibility that the interval being timed was 6 rather than 23 hr, with the transition between light and dark periods acting as a direct discriminative cue signaling the approach of feeding time. However, because Davis and Bardach (1965) found that a prefeeding response could develop under continuous light, we sought to evaluate the consequence of removing light cues on the development of operant temporal discrimination. The effect of continuous light on the goldfish's ability to learn the temporal contingencies of a new feeding time was studied in Experiment 2.

## EXPERIMENT 2

### Method

**Subjects.** Subjects 5, 6, 7, and 8 and their respective companion fish used previously in Experiment 1 served as subjects.

**Apparatus.** The apparatus was that used in Experiment 1. The tank partitions remained in place, and husbandry procedures were carried out as for Experiment 1.

**Procedure.** The lights were set to remain on continuously, and the fish were returned to a 1-hr restricted feeding regime directly follow-

ing the final baseline stage (Stage 4) of Experiment 1. No training or shaping procedure was used. The time of food availability was varied among subjects such that fish that had the dispenser active from 2:00 a.m. to 3:00 a.m. during Stage 2 of Experiment 1 now had it active from 2:00 p.m. to 3:00 p.m., and vice versa. Data were collected over a 3-week period.

### Results

Subject 5 failed to respond during the period of restricted feeding, and lever pressing extinguished. The other 3 subjects showed signs of anticipation within a week of the imposition of the new schedule. The pattern of the mean response rate over a 5-day period (commencing 2 weeks after the new schedule was imposed) is shown for the 3 remaining subjects in Figure 7. The mean level of responding during the 30 min prior to feeding and designated nonfeeding times over this period is given in Table 2.

All data were square-root transformed to stabilize variance, and a repeated measures one-way ANOVA was carried out. There was significantly more lever pressing in the 30 min prior to feeding times than prior to the designated nonfeeding times,  $F(1, 2) = 21.97$ ,  $p < .05$ .

### Discussion

Figure 7 shows that temporal discrimination did develop under a continuous lighting

regime. This is consistent with the findings of Davis and Bardach (1965, Experiment 4) and extends their findings to explicitly operant behavior. The lack of a light cycle seems to have had little effect on the subjects' ability to develop anticipatory responding. It is not possible to say whether behavior could have adapted to the temporal contingencies equally well without the benefit of regular changes in illumination if the fish had never experienced the temporally contingent schedule of Experiment 1; this is a matter that requires further investigation.

### GENERAL DISCUSSION

The contingencies of the present experiments might be considered to be similar to those operating on fixed-interval schedules of reinforcement (Ferster & Skinner, 1957). Consequently, previous findings concerning responding on fixed-interval schedules may help to illuminate the effect of the light cycle used in Experiment 1 on the pattern of anticipatory lever pressing. If the light transitions of Experiment 1 functioned as discriminative stimuli that signaled the beginning of a 6-hr fixed interval, then an increase in the length of the period of anticipatory activity when the 23-hr fixed interval of Experiment 2 was imposed would be consistent with the observed relationship between interval length and response patterns in other species (Ferster & Skinner, 1957; Lejeune, Richelle, Mantanus, & Defays, 1980; Mackintosh, 1974; Shull, 1971). A comparison of Figures 3 and 4 with Figure 7 shows that in Experiment 2, the buildup in activity prior to the feeding times did indeed extend over a longer period (typically 8 hr) than it had during Stage 2 of Experiment 1 (typically 6 hr).

The distribution of responses following prolonged exposure to fixed-interval schedules is more usually described with reference to the postreinforcement pause (Dews, 1978; Ferster & Skinner, 1957; Harzem, 1969) or to the breakpoint between periods of low and high rates of responding (Schneider, 1969). In the present experiments responding continued for a short while following the end of the feeding period, but was then nearly absent until a few hours before the next feeding period was due. At this point an acceleration in response rate occurred that continued up to the feeding time.

Table 2

Number of responses in the 30 min prior to the feeding and nonfeeding periods of Experiment 2.

Subject		Feeding	Nonfeeding
6	<i>M</i>	140.0	0.0
	<i>SD</i>	19.9	0.0
7	<i>M</i>	48.4	0.0
	<i>SD</i>	12.7	0.0
8	<i>M</i>	68.4	5.0
	<i>SD</i>	12.1	7.5

*Note.* Values averaged over the last 5 days of the experiment.

Because the response rate progressively increased during this period of activity, it cannot be described as a typical break-and-run performance (Schneider, 1969). Similarly, the classification of the preceding period of inactivity as a pause would not be strictly equivalent to that applied to shorter intervals (some responding did occur during the period of inactivity). However, if allowance is made for the possibility that the unusual length of the intervals involved may have led to a number of isolated lever presses within what would otherwise be a pause, then finding that this "pause" extended when the interval was extended would also be consistent with findings in the fixed-interval literature.

For conventional fixed-interval schedules, the length of the pause has been described as a negatively accelerating function of increasing interval duration (Lowe, Harzem, & Spencer, 1979; Wearden, 1985). In other words, although the absolute duration of the pause increases with increasing interval length, the proportion of the interval during which responding is absent is smaller for longer interval values. If the difference between the performance observed in Experiment 1 and that observed under the constant lighting of Experiment 2 had indeed been due to an effective lengthening of the fixed interval, the postreinforcement pause in Experiment 2 would be expected to constitute a smaller proportion of the interreinforcement interval than the pause between the time of the light/dark transition and the onset of responding in Experiment 1. The actual values displayed the opposite relationship. In Experiment 2, the postreinforcement pause spanned approximately two thirds of the interval, whereas in Experiment 1 the onset of responding was almost coincident with the light/dark transition. This suggests that

the light cycle did not function simply as a signal for the start of a 6-hr interval in Experiment 1.

The reason for this result may lie in a particular feature of schedules that approximate the solar cycle. Such schedules permit the contribution of circadian timing to the relation between the probability of reinforcement and the passage of time (Boulos & Terman, 1980). For example, rats show more distinct anticipatory lever pressing when food is made available according to a 24-hr rather than a 19- or 29-hr cycle (Bolles & Stokes, 1965). Even when immediate exogenous cues are available, anticipation of a fixed daily feeding period may persist. In an experiment with rats, Terman *et al.* (1984) found that, on a schedule in which 4 hr of reinforcer availability were followed by 20 hr in which lever presses were not reinforced, anticipatory lever pressing was reduced but not eliminated by the provision of auditory cues that commenced only minutes before feeding time. This result was attributed to an interaction between circadian and short-interval timing. A similar interaction might have been responsible for the effect of the light cycle in Experiment 1, in that the light transitions may indeed have served as discriminative stimuli, but the observed pattern of behavior could have arisen from a combination of conventional fixed-interval and circadian timing processes.

Alternatively, it could be that the longer postreinforcement pause seen in Experiment 1 was due to more accurate timing being possible in the presence of a light cycle because, in line with the function suggested by Davis and Bardach (1965), it optimized the synchronization of a circadian pacemaker with the 24-hr cycle, which in turn provided more temporally precise endogenous cues.

If the temporal patterning of responses was dependent on an endogenous circadian rhythm, the time of peak responding would be expected to "free run" in a constant environment (Boulos & Terman, 1980). This condition could have been achieved in Experiment 2 by making the dispensers inoperative following the establishment of anticipation in continuous light. However, as Figures 5 and 6 show, responding dropped to near-zero levels after only a few days when reinforcement was withheld; thus, it is unlikely that enough data would have been available to show any systematic shift in the patterning of responses.

The relationship between chronobiological factors and temporal regulation on operant schedules has received little attention (Lejeune, Richelle, & Mantanus, 1980), and the question of whether the anticipatory behavior shown by the subjects in the present experiments is best characterized as a result of circadian timing, exposure to an unconventional variety of fixed-interval schedule, or indeed, a combination of the two, remains open.

A problem with the present (and all) discrimination experiments is the possibility of a disparity between the subject's performance and its capability. The increase in lever pressing commenced several hours before the feeding times were due. As noted by Ferster and Skinner (1957), a subject with a perfect sense of time should not respond *before* the feeding time at all. It is not clear whether this long buildup was a consequence of a limit on control by the passage of time or of some other factor, such as a greater tendency to activate the lever when increasing hunger had intensified the motivation to feed. The act of pressing the lever requires very little effort, and for a laboratory-housed subject there are few other activities to compete for attention.

There is a potential application for operant temporal discrimination in commercial aquaculture. Acoustic discriminative stimuli have already been used to influence the activity of relatively free-swimming fish. This form of aquaculture is known as recall ranching. In Japan, Fujiya *et al.* (1980) implemented a restocking program that relied on a conditioned tone-food association to keep juvenile farmed fish within the confines of a sheltered bay (away from areas heavily fished by commercial fleets) until they reached a marketable size, and Midding *et al.* (1987) carried out a similar program in Norway. The results of the present experiments suggest that the need for sound-generating equipment in such programs might be attenuated if temporally structured feeding regimes were employed. If this proved to be the case, it might be possible to substitute an accurate timepiece for the sophisticated sound-generating equipment presently required.

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